

FU ORIONIS OUTBURSTS, PREFERENTIAL RECONDENSATION OF WATER ICE, AND THE FORMATION OF GIANT PLANETS

ALEXANDER HUBBARD¹

(Dated: November 8, 2016, Revision: 1.20)
Draft version November 8, 2016

ABSTRACT

Ices, including water ice, prefer to recondense onto pre-existing nuclei rather than spontaneously forming grains from a cloud of vapor. Interestingly, different potential recondensation nuclei have very different propensities to actually nucleate water ice at the temperatures associated with freeze-out in protoplanetary discs. Therefore, if a region in a disc is warmed and then recooled, water vapor should not be expected to refreeze evenly onto all available grains. Instead it will preferentially recondense onto the most favorable grains. When the recooling is slow enough, only the most favorable grains will nucleate ice, allowing them to recondense thick ice mantles. We quantify the conditions for preferential recondensation to rapidly create pebble-sized grains in protoplanetary discs and show that FU Orionis type outbursts have the appropriate cooling rates to drive pebble creation in a band about 5 astronomical units wide outside of the quiescent frost line from approximately Jupiter's orbit to Saturn's (about 4 to 10 au). Those pebbles could be of the appropriate size to proceed to planetesimal formation via the Streaming Instability, or to contribute to the growth of planetesimals through pebble accretion. We suggest that this phenomenon contributed to the formation of the gas giants in our own Solar System.

Subject headings: protoplanetary discs – solid state: volatile – planets and satellites: formation

1. INTRODUCTION

Ices are a major player in planet formation. In decreasing order of condensation temperature, rocky material, water ice, and all other ices each make up about 0.5% of a protoplanetary disc's total mass, and one third of the potential solid mass (Lodders 2003). Accordingly, just outside the water frost line where water is in solid form, the disc has about twice the material available to participate in the growth of solids as inside the frost line. Ice-rimmed dust is also stickier and more collision resilient than bare silicates (Dominik & Tielens 1997), further promoting the collisional growth of solids. The temperature at which the water ice saturation vapor pressure equals the water vapor partial pressure depends on the local number density of water molecules.

Nonetheless, cooling from $T = 170$ K to $T = 166$ K more than halves the saturation vapor pressure (Murphy & Koop 2005). Thus it is reasonable to approximate that the temperature window in which water is not effectively entirely in solid or gaseous phases is extremely narrow, justifying the traditional assumption that the window occurs at $T = 170$ K (Sasselov & Lecar 2000) although this is complicated by disc vertical structure (Podolak & Zucker 2004). Disc regions at larger orbital separations have less ambient material, and therefore must be colder to condense water ice, but the difference in condensation temperatures is small enough that the radial temperature gradient dominates, and the fraction of water condensed rapidly approaches unity outside of the frost line.

We can assume that water vapor is in equilibrium with ice-mantled dust grains as long as the system evolves slowly enough and, crucially, as long as a significant portion of the water ice remains condensed and exposed. If a parcel of gas and ice-mantled dust experiences a temperature fluctuation sufficient to evaporate the ice before cooling, equilibrium cannot be assumed. Homogenous freezing, spontaneous

freezing in the absence of preexisting nuclei, is more difficult than inhomogenous freezing onto existing potential ice nuclei (henceforth IN), and does not occur under the same temperature and pressure conditions as evaporation (Koop et al. 2000). Interestingly however, not all IN are created equal (Cziczo et al. 2013a): at temperatures associated with water freezing in protoplanetary discs, i.e. $T < 170$ K, IN of differing qualities can require saturation ratios SR of factors of several to begin nucleating ice (Cziczo et al. 2013b). Ice is the best surface at condensing more ice, so once mantles are accreted, the differences between ice mantled INs vanish.

If, then, a parcel of gas and ice-mantled dust is heated sufficiently to evaporate all the ice, and then recooled slowly, we can expect the most favorable potential INs to accrete ice mantles first. With those mantles in place, the favored few grains will maintain equilibrium between their water ice surfaces and the water vapor, i.e. a saturation ratio $SR = 1$, preventing water ice from recondensing on the other grains even if they had originally possessed ice mantles. We refer to this process as *preferential recondensation*. If, on the other hand, the parcel is cooled sufficiently rapidly, the rise in SR due to cooling would outpace the drop in SR due to condensation enough for the next tier of INs to also nucleate ice.

One scenario where we would expect preferential recondensation to occur with important consequences is the aftermath of a major accretion event such as an FU Orionis type outburst (Hartmann & Kenyon 1996). FU Orionis events occur early in a protostar's existence and lead to significant disc heating (Cieza et al. 2016). As we will show, during an FU Orionis outburst the entire radial belt from about 4 au to about 10 au could host significant preferential recondensation. By restricting the recondensation to a small subset of dust grains, those grains would grow to sizes associated with both planetesimal formation and pebble accretion (Johansen et al. 2007; Lambrechts & Johansen 2012; Carrera et al. 2015). This provides a pathway to rapidly triggering and promoting the formation of giant planets in the

ahubbard@amnh.org

¹ American Museum of Natural History, New York, NY, USA

outer disc where densities are low and dust coagulation is unlikely to proceed apace.

2. MODEL

As might be expected, there is a vast literature discussing ice formation in the context of terrestrial cloud formation, far beyond the author's expertise and impossible to summarize (Cantrell & Heymsfield 2005; Hoose & Möhler 2012). Protoplanetary discs are however expected to be in a different regime than our atmosphere, with nearly unity IN to water density ratios, and correspondingly large effective IN number densities. Note that, excepting explicit densities of solid grains, any densities we refer to are densities per unit volume of protoplanetary disc gas plus solids. Protoplanetary discs also have sufficiently slow evolution time scales, sufficient turbulent mixing, and sufficiently long molecular mean-free-paths that freeze-out is not expected to be diffusion limited: turbulent mixing and molecular diffusion replenish the water vapor near a dust grain as fast as it is lost to condensation. Further, grains cannot rapidly move out of condensation regions without first growing to meaningful size.

Those large potential IN to water density ratios, combined with relatively slow temperature fluctuations, make homogenous freezing a negligible phenomenon in protoplanetary discs. In the case of the terrestrial atmosphere, one is often in the situation where multiple condensation conditions are met, and which path is taken, such as continued homogenous condensation, or inhomogenous condensation onto newly homogeneously formed INs is a kinetic question (Eidhammer et al. 2009). We can instead assume that the condensation saturation ratios SR are significantly separated for different INs, and that those SR are in turn all significantly below the SR required for homogenous freezing.

In this section we derive a basic model for the kinetics which uses those simplifying assumptions. By assuming that different IN have significantly different SR critical values to begin nucleating ice, we allow condensation to be restricted to a sub-set of IN even if the SR value temporarily rises. Thus, we only need to find the conditions required to avoid large SR fluctuations. More sophisticated models take the time derivation of the saturation ratio SR, e.g. Kärcher & Lohmann (2002). Making effective use of those models would however require a possessing a detailed model of the distribution of the critical SR values for the potential IN actually present.

2.1. Comparing time scales

The saturation pressure of water vapor over ice is approximately (Murphy & Koop 2005):

$$p_{\text{ice}} \simeq \exp(28.9074 - 6143.7/T), \quad (1)$$

where p_{ice} and T are measured in Pa and K respectively. We can use Equation (1) to define

$$\tau_p(\partial_t T) = \frac{p_{\text{ice}}}{\partial_t p_{\text{ice}}} = \frac{p_{\text{ice}}}{\partial_T p_{\text{ice}}} \frac{1}{\partial_t T} \simeq \frac{T^2}{6143.7} (\partial_t T)^{-1}, \quad (2)$$

the time scale for the vapor pressure to change as a function of the heating or cooling rates.

We can compare this time scale τ_p to an equilibration time scale between ice and vapor, which we will quantify through the time required for a vapor water molecule to encounter and expect to stick to an icy target:

$$\tau_c = \frac{1}{\alpha \sigma n_s v_w}, \quad (3)$$

where α is the accommodation coefficient, $\sigma = \pi a^2$ is the collisional cross-section of the icy grains assumed to be spheres of radius a , n_s is the number density of icy grains and

$$v_w = \sqrt{\frac{k_B T}{m_w}} \quad (4)$$

is the thermal speed of a water molecule. The appropriate accommodation coefficient is unclear. Modeling observed cloud formation suggests low values potentially below 10^{-2} , but recent laboratory studies have found $\alpha \gtrsim 0.5$, which value we will use (Skrotzki et al. 2013).

Equation (3) estimates the time-scale on which water molecules freeze out onto ice grains, which means that τ_c is also the time-scale on which the ice partial pressure drops due to recondensation (any drop in partial pressure due to cooling is negligible for our purposes). In a cooling disc, recondensation is rapid enough to keep water ice in rough equilibrium with icy surfaces as long as $\tau_c < \tau_p$. If on the other hand $\tau_c > \tau_p$, then recondensation will lag and the SR will rise, triggering recondensation onto less and less favorable dust grains, causing τ_c to drop over time (more grains to recondense on). Once exactly enough dust grains begin condensing water that $\tau_c = \tau_p$, equilibrium can be maintained, and new grains will not join in.

Assuming ice-vapor equilibration ($\tau_c \lesssim \tau_p$), it takes very little cooling for nearly complete freezing, allowing us to approximate

$$n_s \times \frac{4\pi}{3} \rho_s a^3 = \rho_w, \quad (5)$$

where ρ_s is the approximate solid density of our ice-mantled grains and ρ_w is the fluid density of water molecules in the disc. Note that we have assumed that all the ice nucleating grains are of the same size, and have nucleated sufficient ice to dominate their mass and radius.

Combining Equations (3) and (5), we arrive at

$$\tau_c = \frac{4\rho_s a}{3\rho_w v_w} \alpha^{-1}. \quad (6)$$

Denoting the water-to-gas mass ratio as $\epsilon = \rho_w/\rho_g$, we can rewrite Equation (6) as

$$\tau_c = \frac{4}{3\epsilon} \frac{v_{th}}{v_w} \sqrt{\frac{8}{\pi}} \frac{\tau_E}{\alpha}, \quad (7)$$

where

$$\tau_E = \sqrt{\frac{\pi}{8}} \frac{a \rho_s}{\rho_g v_{th}} \quad (8)$$

is the Epstein regime drag time scale of the dust. The thermal speed of the gas is

$$v_{th} = \sqrt{\frac{k_B T}{m_g}} = \sqrt{\frac{m_w}{m_g}} v_w \simeq 3v_w \quad (9)$$

where $m_g \sim 2$ amu is the gas mean molecular mass.

We can use Equations (2) and (7) to write the condition $\tau_c = \tau_p$ as

$$\Delta T_{\text{Orb}} St \simeq \alpha \frac{T^2}{6143.7} \frac{3\pi\epsilon}{2} \sqrt{\frac{\pi}{8}} \frac{v_w}{v_{th}} \simeq 0.01, \quad (10)$$

where we have used $\epsilon \simeq 0.005$, $v_{th} \simeq 3v_w$, and $T = 160$ K; and ΔT_{Orb} is the change in temperature in degrees Kelvin

over a local orbital period. Equation (10) estimates the largest Stokes number St at which icy grains can recondense ice fast enough to maintain equilibrium with water vapor for a cooling rate defined through ΔT_{Orb} . Alternatively, it defines the fastest cooling rate ΔT_{Orb} at which icy grains with Stokes number St can maintain equilibrium with water vapor.

In Equation (10) the drag time has been non-dimensionalized with the local orbital frequency Ω through the Stokes number of the dust:

$$St \equiv \tau_E \Omega. \quad (11)$$

If a region in the disc heats enough to evaporate the ice and then cools at a rate of about 1 K per orbit, the water vapor is expected to recondense onto a small number of INs, forming dust grains with $St \sim 0.01$, large enough to have significant consequences for planet formation (Johansen et al. 2007; Lambrechts & Johansen 2012; Carrera et al. 2015).

2.2. Latent heat

There is a further complication to estimating ΔT_{Orb} : the latent heat released by water freezing is significant. From Murphy & Koop (2005), we have

$$L_w \simeq 2.7 \times 10^{10} \text{ erg g}^{-1}. \quad (12)$$

Writing

$$\frac{k_B \Delta T}{m_g} = \epsilon L_w, \quad (13)$$

we find that the latent heat is sufficient to correspond to a temperature change of

$$\Delta T \simeq 3 \text{ K}. \quad (14)$$

At a background temperature of $T \sim 160 \text{ K}$ Equation (1) implies that the 3 K temperature difference provided by condensing water vapor in a protoplanetary disc is sufficient to halve the saturation water vapor pressure. If cooling is sufficiently slow for Equation (10) to have significant implications, latent heat could meaningfully further slow the cooling rate.

3. COOLING REGIMES

The details of ice deposition only matter when condensation occurs but is not total, i.e. near a water ice frost line. We examine two cases, static frost lines, and evolving frost lines.

3.1. Static frost line

In the case of a static frost line, we have $\Delta T_{\text{Orb}} = 0$, which in conjunction with Equation (10) would seem to imply the growth of very large ice rimmed grains indeed. However, water vapor will only recondense after being transported across the frost line. Turbulence mixes the water vapor into regions with pre-existing water ice rimmed grains, moving radially at most a turbulent length scale within a turbulent time scale assumed to be approximately the orbital time scale (Fromang & Papaloizou 2006).

Turbulence has a length scale

$$l_t \simeq \sqrt{\alpha_{SS}} H \quad (15)$$

where α_{SS} is the Shakura-Sunyaev α_{SS} (Shakura & Sunyaev 1973), and H the local scale height. We expect the disc background temperature to scale as $R^{-1/2}$ as in a Hayashi (1981)

minimum mass solar nebula (MMSN), so moving one turbulent length scale would correspond to about

$$\frac{\delta T}{T} \simeq \frac{\sqrt{\alpha_{SS}}}{2} \frac{H}{R} \simeq 8 \times 10^{-4} \quad (16)$$

where we have used $\alpha_{SS} \sim 10^{-3}$ and $H/R \sim 0.05$. At a background temperature of $T = 160 \text{ K}$ Equation (16) implies

$$\delta T \sim 0.13 \text{ K}. \quad (17)$$

Thus it is unlikely that water vapor would be able to freeze out, even in an inhomogenous manner, except onto pre-existing ice-mantled dust grains. Even in that case, the approximation that freeze-out or evaporation is total does not apply for such a small δT : while narrow, frost lines are clearly broader than turbulent length scales.

Turbulently mixing two equal volumes of protoplanetary gas and dust outside a frost line, one with ice condensed, and the other, evaporated, will result in the water vapor only recondensing on the pre-existing ice-mantled grains. Even complete recondensation would at most double the mass of the icy grains. From Equation (8) we can see that this would only increase the icy grain stopping time by a factor between $2^{1/3}$ (solid grains growing at constant density) and 2 (highly porous grains growing at constant radius).

Ros & Johansen (2013) showed however that a small number of icy particles outside a frost line will remain there long enough to be mixed into water vapor rich parcels of gas turbulently transported outside the frost line several times, allowing them to grow to significant size. Considerations of differing condensation nuclei qualities only strengthens this conclusion by arguing that the bare IN also carried in the water vapor rich parcels are unlikely to begin to recondense ice before the icy grains freshly mixed into the parcels can do so.

3.2. Evolving frost line

3.2.1. Cooling discs

A more interesting case from our perspective is a cooling disc whose frost line is contracting, causing large radial regions to experience freeze-out. As long as the frost line retreats sufficiently, it will eventually reveal completely dry grains. When global scale cooling rapidly enough Equation (5) applies, and hence Equation (10) holds. That will certainly occur when the frost line retreats faster than turbulence can mix material from both sides of the line. Taking advantage of the very strong temperature dependence of the vapor pressure, we quantify that limit by requiring the frost line to retreat more than a turbulent length scale over a turbulent period, which we estimate as an orbit (Fromang & Papaloizou 2006).

To accurately determine the radial temperature profile of a disc the full radiative transport equations must be taken into account, and discs possess vertically varying thermal structures (Dullemond et al. 2002). The strong dust dependence of radiative transport further complicates the issue in the case of preferential recondensation, when the size of the dust varies rapidly (Inoue et al. 2009). In the case of a cooling disc, we can even expect a dust wall just outside of the frost line, with a jump in the opacity. Given our uncertainties, we adopt the simplifying approximation that $T \propto R^{-1/2}$.

Thus, assuming a disc locally experiencing external irradiation (from the protostar or in the case of an FU Orionis event

the innermost rapidly accreting disc), we can write

$$T^4 = \frac{AL}{R^2} \quad (18)$$

for some constant A , at an orbital position R with external luminosity L . From Equation (1) the frost line temperature varies only slowly with the local gas density. Assuming a frost temperature of $T_f \sim 160$ K, quasi-constant as a function of radius the frost radius is

$$R_f = \frac{\sqrt{AL}}{T_f^2}, \quad (19)$$

and the speed of its retreat is

$$v_f = -\partial_t R_f = -\frac{1}{2T_f^2} \sqrt{\frac{A}{L}} \partial_t L = -\frac{R_f}{2} \partial_t \ln L. \quad (20)$$

The distance ΔR_{Orb} retreated in an orbit is then simply

$$\Delta R_{\text{Orb}} = \frac{2\pi}{\Omega} v_f = \frac{R_f}{2} \frac{\Delta L_{\text{Orb}}}{L}, \quad (21)$$

where ΔL_{Orb} is the change in luminosity in one local orbit. Requiring $\Delta R_{\text{Orb}} > l_t$ we arrive at the constraint that cooling must be faster than

$$\frac{\Delta L_{\text{Orb}}}{L} > 2\sqrt{\alpha_{SS}} \frac{H}{R}. \quad (22)$$

At constant R we can use Equation (18) to write

$$\frac{\Delta T_{\text{Orb}}}{T} = \frac{1}{4} \frac{\Delta L_{\text{Orb}}}{L}. \quad (23)$$

We can use Equation (22) to further determine that cooling outpacing turbulent mixing requires a dimming rate of

$$\frac{\Delta L_{\text{Orb}}}{L} \gtrsim 0.003. \quad (24)$$

The condition for cooling to outpace mixing is that the external (inner disc or protostar) luminosity drops more than 0.3% per local orbit.

3.2.2. Applications to preferential recondensation

Combining Equations (10), (22), and (23) we arrive at

$$St < 2.5 \times 10^{-4} \frac{R}{\sqrt{\alpha_{SS}} H}, \quad (25)$$

where we used $T \simeq 160$ K. For reasonable estimates of $H/R = 0.05$ and $\alpha = 10^{-3}$, Equation (25) becomes

$$St \lesssim 0.08, \quad (26)$$

implying that in the slow cooling limit, preferential recondensation can create quite large icy grains indeed.

We can also combine Equations (10) and (23), estimating $T = 160$ K, to write

$$St = 2.5 \times 10^{-4} \frac{L}{\Delta L_{\text{Orb}}}. \quad (27)$$

We are interested in preferential recondensation if it generates large grains. Arbitrarily setting the lower limit for large at $St \geq 10^{-3}$, Equation (27) implies $\Delta L_{\text{Orb}}/L < 0.25$. Even extreme dimming rates can result in the condensation of respectably large grains. Equation (25) implies that discs that

are cooling sufficiently fast that the frost line outpaces turbulent mixing, but not utterly outclasses it, are expected to see inhomogeneous freeze-out on a small enough fraction of the ambient potential INs so as to condense into large grains.

The range of dimming rates for which we expect preferential condensation onto favored INs to result in large (here $St > 10^{-3}$) grains is therefore

$$3 \times 10^{-3} < \frac{\Delta L_{\text{Orb}}}{L} < 0.25, \quad (28)$$

although variations in α_{SS} or H/R would adjust these dimming rate bounds. Modest differences in the thermal profile ($T \propto R^{-1/2}$) will adjust, but not qualitatively alter, Equation (28). The rates in Equation (28) have potential astrophysical implications, but, especially at the lower end will require long-term monitoring surveys to fully explore (one orbit at 4 au taking 8 years for a $1M_{\odot}$ star). In particular, the bounds match dimming rates associated with FU Orionis, the namesake for FU Orionis type objects (Hartmann & Kenyon 1996). FU Orionis objects undergo violent accretion events, increasing in luminosity by around 6 magnitudes, before dimming on a time scale of about a century.

Recent observations have found that FU Orionis' continuum dimmed by 12% over 12 years, although there is a yet uncertain difference in the dimming rate between shorter and longer wavelengths, similar to previous estimates for BBW 76 and slower than the dimming of V1057 Cyg by a factor of about two (Clarke et al. 2005; Green et al. 2006, 2016). Increasing the luminosity of a Hayashi MMSN by 6 magnitudes would move the water frost line to approximately 45 au, while during quiescence the frost line is closer to 4 au. This estimate has been recently confirmed by Cieza et al. (2016). At

$$R = 4, 9, 16 \text{ au}, \quad (29)$$

the corresponding dimming rates in local orbits would be approximately

$$\Delta L_{\text{Orb}}/L = 8\%, 25\%, 50\%. \quad (30)$$

Out to 10 au, those rates fall within the estimated bounds of Equation (28), suggesting that preferential recondensation was significant from Jupiter to Saturn, and possibly well beyond once the latent heat of water is taken into account. That suggests that as FU Orionis, or a similar object, fades significant preferential water ice recondensation occurs generating icy pebbles.

4. DISCUSSION AND CONCLUSIONS

The aerodynamics of dust grains, as measured through their Stokes number, plays into nearly every aspect of the formation of and potentially also the growth of planetesimals (Lambrechts & Johansen 2012). Preferential recondensation naturally occurs in the aftermath of powerful accretion events such as FU Orionis type events, providing a mechanism to create grains with thick enough icy mantles to be moderately decoupled from the gas ($St \gtrsim 0.01$); a potential observable. Further, different FU Orionis type objects, with differing cooling rates, will have ice-mantled dust grains of differing sizes in their recently cooled regions.

Massive accretion events, FU Orionis outbursts occur early in the life-cycle of a protoplanetary disc with lots of gas left to play with, and are believed to be a common phenomenon with most protostars undergoing several (Hartmann & Kenyon 1996). While the radial extent of the

accretion flow associated with the outburst is unclear, most of the energy is released at the disc's inner edge and it is reasonable to assume a localized engine. We have shown that FU Orionis outbursts naturally combine with preferential recondensation to provide a very rapid (orbital time scale) pathway to creating large ice-mantled dust grains. These pebbles can be of the appropriate size to trigger the Streaming Instability, leading to planetesimal formation very early in the protostar's life potentially at a large orbital separation (Johansen et al. 2007). The pebbles could also supply pebble accretion (Carrera et al. 2015), allowing those early planetesimals to grow to become the cores of gas giants. Thus, evaporation and recondensation could easily have played a major role in the formation of the gas giants in our own solar system; and could play major roles in other forming planetary systems. This reinforces the concept of intermittent thermal processing of solids in protoplanetary discs playing an important role in the process of planet formation (Hubbard & Ebel 2014).

ACKNOWLEDGEMENTS

The research leading to these results was funded by NASA OSS grant NNX14AJ56G.

REFERENCES

- Cantrell, W., & Heymsfield, A. 2005, *Bulletin of the American Meteorological Society*, 86, 795
- Carrera, D., Johansen, A., & Davies, M. B. 2015, *A&A*, 579, A43
- Cieza, L. A., Casassus, S., Tobin, J., Bos, S. P., Williams, J. P., Perez, S., Zhu, Z., Caceres, C., Canovas, H., Dunham, M. M., Hales, A., Prieto, J. L., Principe, D. A., Schreiber, M. R., Ruiz-Rodriguez, D., & Zurlo, A. 2016, *Nature*, 535, 258
- Clarke, C., Lodato, G., Melnikov, S. Y., & Ibrahimov, M. A. 2005, *MNRAS*, 361, 942
- Cziczo, D. J., Froyd, K. D., Hoose, C., Jensen, E. J., Diao, M., Zondlo, M. A., Smith, J. B., Twohy, C. H., & Murphy, D. M. 2013a, *Science*, 340, 1320
- Cziczo, D. J., Garimella, S., Raddatz, M., Hoehler, K., Schnaiter, M., Saathoff, H., Moehler, O., Abbatt, J. P. D., & Ladino, L. A. 2013b, *Journal of Geophysical Research (Planets)*, 118, 1945
- Dominik, C., & Tielens, A. G. G. M. 1997, *ApJ*, 480, 647
- Dullemond, C. P., van Zadelhoff, G. J., & Natta, A. 2002, *A&A*, 389, 464
- Eidhammer, T., DeMott, P. J., & Kreidenweis, S. M. 2009, *Journal of Geophysical Research: Atmospheres*, 114, n/a, d06202
- Fromang, S., & Papaloizou, J. 2006, *A&A*, 452, 751
- Green, J. D., Hartmann, L., Calvet, N., Watson, D. M., Ibrahimov, M., Furlan, E., Sargent, B., & Forrest, W. J. 2006, *ApJ*, 648, 1099
- Green, J. D., Jones, O. C., Keller, L. D., Poteet, C. A., Yang, Y.-L., Fischer, W. J., Evans, II, N. J., Sargent, B. A., & Rebull, L. M. 2016, *ArXiv:1609.01765*
- Hartmann, L., & Kenyon, S. J. 1996, *ARA&A*, 34, 207
- Hayashi, C. 1981, *Progress of Theoretical Physics Supplement*, 70, 35
- Hoose, C., & Möhler, O. 2012, *Atmos. Chem. Phys.*, 12, 9817
- Hubbard, A., & Ebel, D. S. 2014, *Icarus*, 237, 84
- Inoue, A. K., Oka, A., & Nakamoto, T. 2009, *MNRAS*, 393, 1377
- Johansen, A., Oishi, J. S., Mac Low, M.-M., Klahr, H., Henning, T., & Youdin, A. 2007, *Nature*, 448, 1022
- Kärcher, B., & Lohmann, U. 2002, *Journal of Geophysical Research: Atmospheres*, 107, AAC 4
- Koop, T., Luo, B., Tsias, A., & Peter, T. 2000, *Nature*, 406, 611
- Lambrechts, M., & Johansen, A. 2012, *A&A*, 544, A32
- Lodders, K. 2003, *ApJ*, 591, 1220
- Murphy, D. M., & Koop, T. 2005, *Quarterly Journal of the Royal Meteorological Society*, 131, 1539
- Podolak, M., & Zucker, S. 2004, *Meteoritics and Planetary Science*, 39, 1859
- Ros, K., & Johansen, A. 2013, *A&A*, 552, A137
- Sasselov, D. D., & Lecar, M. 2000, *ApJ*, 528, 995
- Shakura, N. I., & Sunyaev, R. A. 1973, *A&A*, 24, 337
- Skrotzki, J., Connolly, P., Schnaiter, M., Saathoff, H., Möhler, O., Wagner, R., Niemand, M., Ebert, V., & Leisner, T. 2013, *Atmospheric Chemistry and Physics*, 13, 4451